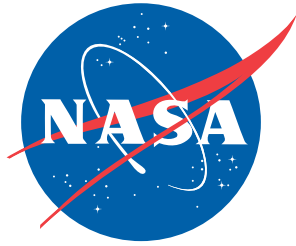


NASA/TM-2010-216729/Volume I  
NESC-RP-08-75



# NASA Aerospace Flight Battery Program

## *Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries*

*David S. Jung and Leonine S. Lee*  
*Goddard Space Flight Center, Greenbelt, Maryland*

*Michelle A. Manzo*  
*Glenn Research Center, Cleveland, Ohio*

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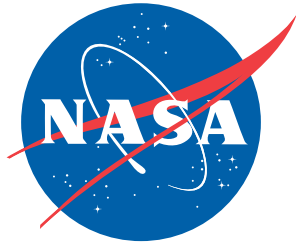
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Space Administration

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August 2010

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# **NASA Aerospace Flight Battery Program**

## **Part 3: Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries**

### **Volume I: Technical Assessment Report**

February 18, 2010


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## Report Approval and Revision History

NOTE: This document was approved at the February 18, 2010, NRB. This document was submitted to the NESC Director on February 23, 2010, for configuration control.

Approved Version:	<i>Original Signature on File</i>	2/24/10
1.0	NESC Director	Date


Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Ms. Michelle A. Manzo, Chief, Electrochemistry Branch, Glenn Research Center	02/18/10

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## **Volume II: Appendices (stand-alone volume)**

- Appendix A. Electrical Testing and Destructive Physical Analysis of Nickel-Hydrogen Cells with Various Storage Histories
- Appendix B. Analysis of Stored Nickel-Hydrogen Battery Cells
- Appendix C. Accelerated Cycle Test Report



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## **Volume I: Technical Assessment Report**

### **1.0 Notification and Authorization**

The National Aeronautics and Space Administration (NASA) Aerospace Flight Battery Systems Working Group (NAFBSWG) was chartered within the NASA Engineering and Safety Center (NESC) on October 5, 2006. Under this charter NAFBSWG was authorized by Mr. Ralph R. Roe, the NESC Director, at the NESC Review Board (NRB) to develop an annual plan to address critical battery-related issues for the Agency and the aerospace community. Ms. Michelle Manzo, Chief of the Electrochemistry Branch at Glenn Research Center (GRC), serves as Chair of the NAFBSWG.

The Initial Plan was presented to the NRB on January 25, 2007. It involved a series of tasks addressing pressing issues related to aerospace battery implementation. The Final Report for Year 1 (Part 1) was approved by the NRB on July 10, 2008. The Final Report for Year 1 (Parts 2 and 3, Vols. I and II each) were approved by the NRB on February 18, 2010.

The key stakeholders for this assessment are the Exploration Systems Mission Directorate (ESMD), Science Mission Directorate (SMD), and Space Operations Mission Directorate (SOMD).

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## 2.0 Signature Page

Submitted by:

*Team Signature Page on File – 5/24/10*

\_\_\_\_\_  
Mr. David S. Jung                      Date

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Mr. Leonine S. Lee                      Date


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Ms. Michelle A. Manzo                      Date

Significant Contributors:

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Dr. Hari Vaidyanathan                      Date

\_\_\_\_\_  
Dr. Albert H. Zimmerman                      Date

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analysis, and inspections.

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### 3.0 Team List

Name	Discipline	Organization/Location
<b>Core Team</b>		
Michelle Manzo	NESC Lead	GRC
Jeff Brewer	Electrical Power	MSFC
Ratnakumar Bugga	Electrochemistry	JPL
Penni Dalton	Electrochemistry	GRC
Eric Darcy	Electrochemistry	JSC
Judith Jeevarajan	Electrochemistry	JSC
David Jung	Electrochemistry	GSFC
Leonine Lee	Electrochemistry	GSFC
Barbara McKissock	Electrochemistry	GRC
Thomas Miller	Electrochemistry	GRC
David Olsen	Electrical Power	KSC
Gopalakrishna Rao <sup>1</sup>	Electrochemistry	GSFC
Concha Reid	Electrochemistry	GRC
Hari Vaidyanathan	Electrochemistry	Lockheed Martin
Albert Zimmerman	Electrochemistry	The Aerospace Corporation
Pamela Throckmorton	MTSO Program Analyst	LaRC
<b>Administrative Support</b>		
Terri Derby	Project Coordinator	LaRC/ATK
Donna Gilchrist	Planning and Control Analyst	LaRC/ATK
Carolyn Snare	Technical Writer	LaRC/ATK


### 3.1 Acknowledgements

**In Memoriam:** This report is dedicated to the memory of our dear colleague Dr. Gopalakrishna (Gopal) Rao. Dr. Rao supported the Power Systems Branch at Goddard Space Flight Center (GSFC) for 19 years until his untimely death on May 15, 2008.

The study was directed by Dr. Rao and his assembled team consisting of:

- Lockheed Martin (LM)/Communications Satellite (COMSAT) Corporation (LM/COMSAT) technical services (Dr. Hari Vaidyanathan) for electrical characterization and destructive physical analysis (DPA).
- The Aerospace Corporation (TAC) (Dr. Albert Zimmerman) for gas analysis and nickel precharge measurement.

<sup>1</sup> Dr. Gopalakrishna Rao served as a core member of this team until his death on May 15, 2008.


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- Naval Surface Warfare Center/Crane Division (NSWC/CD) (Mr. Harold Brown) for accelerated low Earth orbit (LEO) cycle testing.

GSFC, under Dr. Rao's leadership, was the implementing organization for this task. Mr. David Jung, Mr. Leonine Lee, Dr. Hari Vaidyanathan, and Ms. Michelle Manzo completed this report after Dr. Rao's passing.

The assessment team would like to specifically acknowledge contributions from the following:

- Financial/Contracting: Ms. Pam Throckmorton and Ms. Loutricia Johnson.
- The support team from Alliant Techsystems, Inc. (ATK) at Langley Research Center (LaRC) provided excellent support: Ms. Terri Derby for her efforts in meeting coordination and documentation, and Ms. Carolyn Snare and Mr. Eric Pope for technical editing.
- Peer Reviewers: Mr. George Dakermanji, Mr. Mitchell Davis, Mr. Steve Gentz, Mr. Oscar Gonzalez, Dr. Chris Iannello, Mr. Denney Keys, and Mr. Tim Trenkle.

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## 4.0 Executive Summary


In the summer of 2006, the National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) requested that all Super Problem Resolution Teams (SPRTs) (now called Technical Discipline Teams (TDTs)) be solicited for proposals for discipline advancing work. Guidance for proposals included the identification of tasks which address activities that no single program, project, or organization may be able (or reasonably expected) to fund, but where critical knowledge (such as fundamental understanding, a specification, basis for risk assessment, etc.) was lacking. The NASA Aerospace Flight Battery Systems Steering Committee was approached to develop a response to this request. Relevant battery-system issues of concern were identified and prioritized. Tasks aimed at addressing the most critical of these persistent, Agency-wide technical problems were identified. These tasks became the basis of the proposal (NESC PL-07-02/06-069-I NASA Aerospace Flight Battery Systems Working Group (NAFBSWG) Annual Plan) that was accepted by the NESC Review Board (NRB) on October 5, 2006.

At the same time, the NAFBSWG was chartered within the NESC. The NAFBSWG was tasked to complete these tasks, and to propose future work to address battery-related, Agency-wide issues. In its first year of operation, this effort addressed various aspects of the validation and verification (V&V) of aerospace battery systems for NASA missions. NAFBSWG members performed studies, discussed issues, and in many cases, tested programs to generate recommendations and guidelines to reduce risk associated with implementing battery technology in the aerospace industry.

The reporting on these tasks has been split into three Parts, as identified below<sup>2</sup>. The subsequent Final Report for this assessment has also been split into three documents, one for each Part:

- 1) Part 1: Generic Safety, Handling, and Qualification Guidelines for Lithium-Ion (Li-Ion) Batteries (NESC Report Number RP-08-75)
  - a. Li-Ion Performance Assessment
  - b. Generation of a Guidelines Document that Addresses Safety and Handling and Qualification of Li-Ion Batteries (a general guidelines document was developed that was supplemented by the following studies addressing specific Li-Ion batteries concerns)
    - i. Definition of Conditions Required for Using Pouch Cells in Aerospace Missions

<sup>2</sup> Current order of outline and Part numbers are different from original outline in Part 1 of Final Report. Part 1 is now Part 2, Part 2 is now Part 3, and Part 3 is now Part 1. The current Final Report Part 1 documents (Vols. I and II), follow the updated order, reflected in the outline shown above.

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- ii. High-Voltage Risk Assessment: Limitations of Internal Protective Devices in High-Voltage/High-Capacity Batteries using Li-Ion Cylindrical Commercial Cell
  - iii. Definition of Safe Limits for Charging Li-Ion Cells
  - c. Availability of Source Materials for Li-Ion batteries
  - d. Technical Communications Related to Aerospace Batteries (NASA Battery Workshop)
- 2) Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements<sup>3</sup>

### 3) Part 3: Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries

This document is Part 3 of the Final Report and focuses on the **Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries**. Assessment 06-069-I Final Report Part 1 is complete and has been catalogued as NESC Report RP-08-75. All three Parts of the Final Report collectively present the results of the NAFBSWG efforts that were initiated in Fiscal Year 2007.


## 4.1 Part 3: Wet Life of Nickel-Hydrogen Batteries

The majority of current NASA long life/low Earth orbit (LEO) missions (including the Hubble Space Telescope (HST) and the International Space Station (ISS)) uses Ni-H<sub>2</sub> batteries as the spacecraft energy storage system. Unplanned launch delays often result in the use of batteries for NASA missions that have exceeded their recommended wet life of 3–5 years. One example is the HST cell/battery which had a wet life exceeding 9 years by the time of the 2009 refurbishment mission. Storage and handling of flight cells and batteries are critical. Activated cells subjected to storage under uncontrolled, ambient conditions for more than 6 months observed degradation in capacity, loss of high-rate discharge capability, and second plateau development. The impact of extended wet life on the electrical performance of Ni-H<sub>2</sub> batteries and the degradation of the cell components is not well understood.

### 4.1.1 Mitigation

This study researched and collected data related to Ni-H<sub>2</sub> cells and batteries with known storage lives and conditions. The technical approach consisted of performing capacity checks, destructive physical analysis (DPA), gas analysis, Ni precharge assessment, and life-cycle testing on the cells obtained for this assessment. Correlations between storage conditions, data generated from the above analyses, and capacity and performance retention contributed to recommendations on how to assess the quality and condition of Ni-H<sub>2</sub> cells to determine their suitability for NASA missions.

<sup>3</sup> Title formally identified as Recommendations for Binding Procurements.

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## 5.0 Assessment Plan

The NAFBSWG provided a framework to address manufacturing and performance issues related to flight battery systems technology and applications for NASA missions that require batteries. This assessment supported the V&V of aerospace-battery systems for NASA missions. It enabled the implementation and execution of critical test programs to reduce risk by addressing wide-ranging technology issues. These issues affect the safety and success of future NASA missions.

The objectives of the NAFBSWG were:

- Develop, maintain, and provide tools for the validation of aerospace battery technologies
- Accelerate the readiness of technology advances and provide infusion paths for emerging technologies
- Provide the database and guidelines for technology selection that can be used across mission directorates
- Disseminate validation and assessment tools, along with quality assurance and availability information, to the NASA and aerospace battery communities
- Provide problem-resolution expertise and capability within the Agency and the aerospace community

During this assessment, it was determined that the analysis could be split into three distinct Parts<sup>4</sup>:

1. Part 1: Generic Safety, Handling, and Qualification Guidelines for Lithium-Ion (Li-Ion) Batteries (NESC Report Number RP-08-75)
2. Part 2: Recommendations for Technical Requirements for Inclusion in Aerospace Battery Procurements<sup>5</sup>


### 3. Part 3: Wet Life of Nickel-Hydrogen (Ni-H<sub>2</sub>) Batteries

As a result, the Final Report was also divided into three separate documents, each addressing one of the three Parts. This document addresses **Part 3**.

The technical approach for this battery wet life study involved the identification of Ni-H<sub>2</sub> cells with known and varied histories that could be studied to evaluate their performance as a function of storage time and conditions. Thirty-seven cells with wet life histories of 1–13 years were identified for evaluation in this study. All of the cells tested were manufactured by Eagle Picher. Following activation and acceptance testing, the cells were stored at  $0 \pm 5^{\circ}\text{C}$ . Only one of the

<sup>4</sup> Current order of outline and Part numbers are different from original outline in Part 1 of Final Report. Part 1 is now Part 2, Part 2 is now Part 3, and Part 3 is now Part 1. The current Final Report Part 1 documents (Vols. I and II), follow the updated order, reflected in the outline shown above.

<sup>5</sup> Title formally identified as Recommendations for Binding Procurements.

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cells, #104, had been subjected to extensive cycling. The older cells may have been subjected to periodic limited cycling for capacity verification but the actual histories are not known. Twenty-seven of the cells were selected for electrical characterization/DPA studies at LM/COMSAT and TAC. These cells included ten cells from the ISS manufacturing lot, two cells from the Terra program, four cells (two each) from the HST/United States (US) Government (USG) programs, seven cells from commercial programs, three cells from the Aqua program, and one Intelsat cell that had been cycled in a geosynchronous Earth orbit (GEO) regime for 9 years. An additional ten cells were selected for life-cycle tests at NSWC/CD, and four more cells were subjected to thermal imaging analyses at GSFC.


All but one of the 27 cells selected for characterization, precharge analyses, and DPA (cell #104) were electrically characterized at LM/COMSAT. Additional analyses conducted at LM/COMSAT on 11 of the cells included DPA and analyses to determine: the degradation in the positive plates, negative plates, and separator; the initial precharge and electrolyte distribution; and the gas analyses. Eleven companion cells with similar construction and storage histories were similarly evaluated at TAC. Testing at TAC included electrical characterization.

Table 5.0-1 is a listing of the articles analyzed for the DPA/characterization studies. Cells with capacities < 100 Ah were the 3.5-inch-diameter cells and those with capacities > 100 Ah were the 4.5-inch-diameter cells. The laboratory responsible for the DPA, gas analysis, and precharge measurements is noted for those cells that underwent these analyses. The highlighted blocks in the table under the 'Precharge' column are indicative of cells that underwent both electrical and chemical analyses of Ni precharge at TAC.

***Table 5.0-1. Summary of Articles for DPA/Characterization Studies***

S/N	Program	Capacity	Activation Date	Gas Analysis	Precharge	DPA
5	Aqua	160	1997	COMSAT	COMSAT	COMSAT
15	Aqua	160	1997	TAC	TAC	
89	Aqua	160	1997			
1038	Comm	120	1997	TAC	TAC	
1052	Comm	120	1997	COMSAT	COMSAT	COMSAT
1238	Comm	120	1997	COMSAT	COMSAT	COMSAT
1997	Comm	120	1999	TAC	TAC	
2204	Comm	120	2000			
2749	Comm	120	2004	TAC	TAC	
2925	Comm	120	2006			




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605	HST	90	2000	COMSAT	COMSAT	COMSAT
718	HST	90	2000	TAC	TAC	
102	USG	90	1997	COMSAT	COMSAT	COMSAT
165	USG	90	1997	TAC	TAC	
224	ISS	81	1994	COMSAT	COMSAT	COMSAT
306	ISS	81	1995	TAC	TAC	
501	ISS	81	1996			
972	ISS	81	1997			
1728	ISS	81	1998	COMSAT	COMSAT	COMSAT
2170	ISS	81	2000	TAC	TAC	
2188	ISS	81	2001	COMSAT	COMSAT	COMSAT
2517	ISS	81	2002			
2932	ISS	81	2004	TAC	TAC	
2933	ISS	81	2004	COMSAT	COMSAT	COMSAT
122	Terra	50	1995	COMSAT	COMSAT	COMSAT
262	Terra	50	1996	TAC	TAC	
104	GEO Cycled	50	?	TAC	TAC	

Accelerated LEO studies consisted of two, five-cell packs that were subjected to accelerated testing at 60-percent depth of discharge (DOD). The cells were cycled in a 90-minute LEO orbit that consists of 30 minutes of discharge and 60 minutes of charge, at 10°C with voltage/temperature (VT) charge control.

The packs were tested at the Naval Systems Warfare Center, Crane Division (NSWC/CD) battery test facility. The packs were designated 7604W and 7605W. A third pack, 7606W, was added as a replacement when Pack 7604W was damaged during the life-cycle test due to an equipment failure after ~1,200 cycles. Table 5.0-2 lists the cells selected for the LEO cycling evaluation.

Pack 7604W contained five Eagle-Picher 90-9 cells from USG programs, activated in March 1997. The cells were built at the Eagle-Picher/Joplin plant using positive electrode plaque (from the Eagle-Picher/Colorado Springs plant) that was impregnated at the Joplin plant by the C-Street (Joplin plant) process. Life-cycle testing on these cells started in August 2007.

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Pack 7605W contained five 81-Ah Eagle-Picher cells manufactured for ISS and activated on May 27, 1997. The initial evaluation on these cells was completed on October 26, 2007, with life-cycle testing starting in November 2007.

Pack 7606W contained five Eagle-Picher 90-9 cells from USG programs. Four of the cells were activated in April 1995 and the fifth cell was activated in March 1997. Life-cycle testing on these cells was initiated in May 2008.

*Table 5.0-2. Summary of Articles for Life-Test Studies*

Pack No.	Cell Identification	Activation Dates
7604W	Five 90-Ah Cells—USG Programs	March 1997
7605W	Five 81-Ah ISS Cells	May 1997
7606W	Five 90-Ah Cells—USG Programs	Cells 1,2,3, and 5—April 1995; Cell 4—March 1997

## 6.0 Problem Description and Analysis and Risk Assessment


### 6.1 Problem Description and Analysis

Wet life storage of cells/batteries has been the subject of intense debate ever since problems with capacity fading and degraded voltage profiles surfaced in the cells/batteries that had been stored due to unscheduled launch delays. One recommendation of the early studies [refs. 2, 3, 4, 5] was to minimize storing cells at room temperature. The number of flight programs affected by unplanned storage of batteries for several years, necessitated the investigation into the effects of extended stand or wet life.

The purpose of the present task was to study a large number of cells with varying wet-storage lives to better understand the effects of wet life on performance and a cell's ability to meet mission requirements. The cells were studied to determine whether or not the degradation of components had accelerated; to evaluate the changes in response to thermal conditions when the cells were charged and discharged; and to perform electrical characterization, DPA, and life-cycle testing of cells with varying wet lives.

### 6.2 Risk Assessment

Ni-H<sub>2</sub> cells are best stored discharged at  $0 \pm 5^{\circ}\text{C}$ . Nickel precharge was adopted as the standard design practice for Ni-H<sub>2</sub> cells in the mid 1980s. For cells of this design, capacity is best maintained if the cells are left in the discharged condition during the storage period. However, even in a discharged condition at a lowered temperature, degradation will occur. This study focused on determining the severity of that degradation and assessing the flightworthiness of cells that have been stored for extended periods.

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## 7.0 Data Analysis

### 7.1 Electrical Characterization and Destructive Physical Analysis— Lockheed Martin/COMSAT Corporation

The effect of wet life on the performance of Ni-H<sub>2</sub> cells was investigated through electrical characterization testing and DPA. The cells selected for this assessment were kept in cold storage ( $0 \pm 5^{\circ}\text{C}$ ) after the initial acceptance testing. The 26 cells analyzed at LM/COMSAT belonged to NASA/aerospace programs such as Terra, ISS, USG, commercial, and HST.

Following the activation and acceptance testing, the selected cells were stored discharged, at  $0 \pm 5^{\circ}\text{C}$ . The HST 81-Ah cells (Serial Numbers (S/Ns) 605 and 718) were stored dry for 4.5 years prior to their activation in 2000. Some of the cells were periodically removed from storage for capacity evaluation/maintenance cycling and electrical characterization (consisting of stabilizing the cells at  $0^{\circ}\text{C}$ ,  $10^{\circ}\text{C}$ , and  $20^{\circ}\text{C}$  and measuring the charge voltage profiles, discharge capacity, charge retention, voltage rise from the discharged condition, and cell reversal voltage). A summary of the test results from the performance characterization appears in Table 7.1-1.

*Table 7.1-1. Cell Performance Data*

Cell ID	Program	Cell Capacity (Ah)	Activation Date	10°C CAPACITY DATA				Reversal Voltage (V)	Voltage rise after 1 hr (V)*
				Capacity to 1 V (Ah)	Capacity in 2nd plateau (%)	Capacity from resistor drain (Ah)	Charge Retention (%)		
122	Terra	50	Jan-95	66.9	NA	1.1	90.3	-0.28	0.095
262	Terra	50	Jan-96	64.7	NA	1.3	90.5	-0.29	0.084
224	ISS	81	Oct-94	100.5	5.5	8	85.9	-1.43	0.134
306	ISS	81	Apr-95	104.9	5.5	2.3	87.6	-0.78	0.121
501	ISS	81	Oct-96	109	2.2	1.1	84.7	-0.37	0.165
972	ISS	81	Jul-97	103.6	NA	1.4	88.8	-0.31	0.11
1728	ISS	81	Dec-98	100.6	NA	3.5	89.8	-0.33	0.091
2170	ISS	81	Jan-00	105.1	NA	1.2	88.9	-0.32	0.086
2188	ISS	81	Oct-01	101.7	NA	1.2	88.9	-0.32	0.134
2517	ISS	81	Aug-02	100	NA	1	88.5	-0.3	0.095
2932	ISS	81	Jun-04	106	NA	1.4	88.6	-0.31	0.084
2933	ISS	81	Jun-04	105.6	NA	1.1	88.7	-0.31	0.105
102	USG	90	Mar-97	103.3	NA	0.6	87.2	-0.38	0.08
165	USG	90	Mar-97	102	NA	0.7	87.3	-0.36	0.078

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605	HST	90	Aug-00	94.7	9.2	3.8	82.2	-1.52	0.061
718	HST	90	Aug-00	95.1	9.1	3.5	84.6	-1.51	0.08
1038	Comm	120	Apr-97	153.2	NA	1.5	87.9	-0.41	0.063
1052	Comm	120	May-97	147.9	4.3	7.2	86.7	-1.53	0.06
1238	Comm	120	Aug-97	151.2	NA	1.7	87.3	-0.42	0.089
1997	Comm	120	Aug-99	139.9	NA	19.1	85.1	-1.23	0.072
2204	Comm	120	Feb-00	146.1	NA	1.3	87.3	-0.36	0.108
2749	Comm	120	Feb-04	139.8	NA	1	87.3	-0.33	0.091
2925	Comm	120	Aug-06	143.4	NA	3.1	87.1	-0.32	0.13
5	Aqua	160	Nov-97	200.8	NA	3.1	85.5	-0.39	0.018
89	Aqua	160	Nov-97	200.8	NA	3.4	84.2	-0.4	0.016
15	Aqua	160	Nov-97	193.6	NA	1.8	87.7	-0.33	0.015
			*After resistor drain to 10 mV						

Eleven of the cells were subjected to additional testing and 11 companion cells were sent to TAC for parallel testing. The cells retained for DPA at LM/COMSAT were first subjected to gas analysis. In this test, the cells were in a discharged state and their fill tubes were opened to determine the presence of gas. Gas was not detected in any of the cells, providing a preliminary indication that the cells maintained their nickel precharge.

The cells were then dissected to extract the electrode stack and examine the condition of the components including structural features, contaminants, and workmanship. Physical measurements were made. The positive plates, negative plates, separators, and electrolyte were analyzed for properties such as positive active material composition; loading and coefficient of utilization; positive swelling and blistering; negative plate polarization; separator absorbency; and electrolyte concentration, content, and distribution.

The inspection results are summarized below:

- Capacity Evaluation: Cell capacity was not impacted by long wet life up to 13 years. The capacity of each cell in this study was measured following storage for varying lengths of time. All capacities were > 19 percent higher than the rated capacity of the cells, which is consistent with values for new cells.
- Charge Retention: Cells in this study retained 82–90.5 percent of the charge following a 72-hour open-circuit stand, which indicates the absence of internal shorts in the cells.
- Second Plateau: Ni-H<sub>2</sub> cells exhibit a low-voltage plateau in their discharge curves when the cells have been stored for an extended period, cycled extensively, or been subjected to uncontrolled handling (e.g., stored partially charged, stored at temperatures > 10°C, or subjected to overcharge at temperatures > 10°C or at rates higher than C/10). Seven of

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the cells evaluated in this study exhibited second plateaus showing capacity below 1 V. These included three ISS cells, two HST, and two 120-Ah cells from commercial programs with longer wet life.


- Reversal voltage and gas analysis showed that Ni precharge was maintained for all of the stored cells. In general, the reversal voltage exhibited by cells with Ni precharge is  $< -0.35$  V. The reversal voltage on most of the cells in this study measured  $-0.35$  V. Cells with longer wet life measured voltages as follows: ISS cells (S/Ns 3-224 and 4-306) measured  $-1.43$  V and  $-0.78$  V, respectively; HST cells (S/Ns 10-605 and 11-718) measured  $-1.51$  V; and the commercial 120-Ah cell (S/N 22-1997) measured  $-1.23$  V. None of the cells had a voltage  $> -0.35$  V, which would be indicative of  $H_2$  precharge.
- The positive plates showed various degrees of blistering. There was no clear correlation between the length of time the cells were stored and the size or severity of the blistering.
- Coefficient of positive material utilization was unchanged.
- Cells stored discharged at low temperatures ( $0 \pm 5^\circ\text{C}$ ) maintained the electrical performance and Ni precharge for as many as 13 years of wet life.

For more information on the LM/COMSAT report, see Appendix A in this Final Report, Part 3, Volume II.

## 7.2 Electrical Characterization and Ni Precharge Determination—The Aerospace Corporation

Ten cells that had been evaluated at LM/COMSAT were sent to TAC for electrical characterization, gas analysis, and Ni precharge determination. The eleventh cell evaluated at TAC was not electrically characterized at LM/COMSAT. This was an Intelsat cell that had been GEO-cycled for 9 years prior to this assessment and had  $H_2$  precharge due to cycling. The cycled cell was added for comparison purposes.

Electrical characterization at TAC consisted of stabilizing the cells at  $0^\circ\text{C}$ ,  $10^\circ\text{C}$ , and  $20^\circ\text{C}$ , and measuring the charge voltage profiles and discharge capacity, charge retention, voltage rise from the discharged condition, and cell reversal voltage. Gas samples were collected from the cells and then quantitatively analyzed using a residual gas analyzer mass spectrometer. Six of the cells were selected for further analysis that included electrochemical and chemical Ni precharge measurements.

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The summary results were:


- The capacity of the cells, stored discharged at  $0 \pm 5^{\circ}\text{C}$ , was not impacted by wet life exposure up to 12 years.
- Reversal voltage and gas analysis showed that Ni precharge was maintained in all cells except in the Intelsat cell which had undergone 9 years of cycling. The Intelsat cell contained  $\text{H}_2$  gas at 40 psia.
- There was general agreement between the Ni precharge analyses performed at LM/COMSAT and the two methods used at TAC.

For more information on the results of the analyses performed at TAC, see Appendix B of this Report, Part 3, Volume II.

### **7.3 Accelerated Low Earth Orbiter Cycle Testing—Naval Surface Warfare Center/Crane Division**

The objective of this portion of the assessment was to evaluate the long-time performance of wet-stored cells under accelerated cycle test conditions. Ten cells were selected for this test; five ISS 81-Ah cells and five USG 90-Ah cells were assembled into two packs (see Table 5.0-2 for pack descriptions). All cells had been stored discharged at  $0 \pm 5^{\circ}\text{C}$  and had minimal cycling beyond the Acceptance Test Procedure cycles. Electrical characterization data were comparable to the LM/COMSAT and TAC results. The LEO test conditions were 60-percent DOD,  $10^{\circ}\text{C}$ , in a simulated 90-minute orbit with 30 minutes for discharge and 60 minutes for charge, and VT-compensated charge control with taper. As of November 2009, Pack 7605W (containing the ISS cells) had completed ~12,000 nominal cycles and had started to show signs of decay after 11,500 cycles. The USG cell pack (7606W) had completed ~9,000 cycles. Pack 7606W experienced low end-of-discharge voltages and cell divergence at 7,200 cycles. The DOD was reduced from 60- to 15-percent DOD, a level more representative of an HST profile.

There were limited data to determine if wet life had affected cycle performance of these cell packs. A NASA Battery Workshop Presentation [ref. 6] from 2008 reported on the cycle performance of similar vintage HST cells with wet lives that varied between 1 and 6 years. Packs cycled at 60-percent DOD demonstrated between 7,000 and 17,500 cycles to the 1.0-volt cutoff. The packs in this study had longer wet lives and cycled  $> 7,000$  cycles before reaching the 1.0-volt cutoff. With the performance demonstrated to date there are no clear indications of issues resulting from the prolonged storage. These test packs generally exhibit nominal performance comparable with packs that have not been stored for extended times. However, the tests are still ongoing and there is no means of determining the long-time, in-orbit performance effects of prolonged storage without testing for five years or to failure, whichever comes first. For more information on these tests, see the NSWC/CD Test report, Appendix C of this Final Report, Part 3, Volume II.

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## 7.4 Summary

Twenty-six cells which had been stored between 2 and 13 years, under controlled conditions (discharged and at temperatures  $< 10^{\circ}\text{C}$ ), were evaluated at LM/COMSAT and TAC. Their electrical characteristics were generally indicative of healthy cells, with all cells exhibiting measured capacities in excess of their rated capacity. Electrical characterization, gas analysis, and precharge determination indicated all the cells, except the cycled Intelsat cell (with  $\text{H}_2$  presence due to cycling), maintained Ni precharge. However several of the cells did show signs of degradation. Six cells showed a second plateau and six of the cells stored for longer (or older) than 5 years showed more than the normal negative ( $< -0.35\text{ V}$ ) values for the reversal potential.

The destructive physical analysis showed no abnormalities at the stack level. Electrolyte distribution was normal. The positive plates showed blisters but the number and size of blisters did not appear to be a function of the length of the wet life.

The accelerated LEO testing of 10-year ISS and USG cells, as of November 2009, had completed  $> 8,500$  nominal cycles.

In summary, a Ni- $\text{H}_2$  cell/battery with up to 13 years of wet life, stored in a discharged condition at cold temperatures ( $0 \pm 5^{\circ}\text{C}$ ), can retain Ni precharge, maintain acceptable capacities, and cycle for  $> 7,000$  cycles at 60-percent DOD.


## 8.0 Findings, Observation, and NESC Recommendations

### 8.1 Findings

The following Findings related to wet life were identified:

- F-1.** Ni- $\text{H}_2$  cell capacity, charge retention, and voltage rise were not influenced by storage periods up to 13 years after activation when cells were stored uncycled, in a discharged condition, at  $0 \pm 5^{\circ}\text{C}$ .
- F-2.** Second voltage plateau occurred in cells with longer wet life.
- F-3.** There was no apparent correlation between the number and size of blisters noted on the positive plates and the length of time the cells were stored.
- F-4.** Coefficient of positive material utilization was unchanged as a function of wet life, indicating that positive active material maintains its activity even with extended storage periods.



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- F-5.** Electrical signatures from the reversal test were the most definitive in detecting the type of precharge in the cells. Cells with reversal voltages  $< -0.35$  V consistently exhibited Ni precharge.
- F-6.** Open-circuit voltage recovery provided an indication of the presence of H<sub>2</sub> precharge. In general, higher recovery voltages are associated with higher precharge levels.
- F-7.** The stored, uncycled cells maintained some level of Ni precharge, but the levels were significantly lower than those usually seen in new cells. Typical values for new cells are 18–25 percent; the stored, uncycled cells had levels as low as 4 percent.

## 8.2 Observation

The following Observation related to wet life was identified:

- O-1.** The long-term effects of extended storage on cycle performance in mission conditions have not been fully evaluated.

## 8.3 NESC Recommendations


The following NESC Recommendations were identified and directed toward the key stakeholders unless otherwise identified:

- R-1.** Representative cells from lots that have been stored for  $> 6$  years should undergo characterization and precharge testing to validate characteristics that demonstrate acceptable performance. (*F-1, F-2, F-5, F-6, F-7*)
- R-2.** Representative cells from lots that have been stored for  $> 8$  years should undergo accelerated LEO testing to validate characteristics that demonstrate acceptable performance. (*O-1*)
- R-3.** An analysis of the relationship between periodic cycling and the maintenance of Ni precharge is recommended to fully understand these effects. (*F-1, F-2, F-5, F-6*)

## 9.0 Definition of Terms


Accelerated Cycle Test	A cell or battery is tested by being charged and discharged under conditions more stringent than those expected in its proposed
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application in order to produce premature degradation and estimate its normal operating life.


Acceptance	A determination that the product meets the design specifications.
Battery	One or more electrochemical cells that are electrically connected.
Capacity	The number of ampere-hours that can be delivered by a fully charged cell or battery under the specified conditions.
Cell	A single-unit device within one cell case that transforms chemical energy into electrical energy at characteristic voltages when discharged.
Charge Retention	The fraction of a cell's or battery's full capacity under specified discharge conditions that is still available after it has been stored.
Cold Storage	For batteries that are not in use, long-term storage during which the temperature and humidity environments are controlled and temperature is below ambient temperature.
Cycle	A discharge (capacity of the battery is used) and subsequent recharge (capacity of the battery is restored) of a rechargeable battery.
Depth of Discharge	The ratio of the capacity removed from a cell or battery under specified conditions to its rated capacity.
Destructive Physical Analysis	The process of opening up a cell, removing material from it, and analyzing the changes that have occurred.
Electrode	The location where the electrochemical reactions occur.
Electrolyte	The medium which transports ions between electrodes.
Energy	Launch, transfer orbit, and on-orbit battery energy and energy reserve requirements are flowed down from the Electrical Power Subsystem specification for the entire mission life. Battery energy is equal to the integral of the product of discharge current and voltage, where $I_d$ , a positive value, is the discharge current, and $V_d$ , a positive value, is the discharge voltage. The limits of integration

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are from start of discharge to either the minimum power subsystem battery voltage limit, or when the first cell reaches the lower cell voltage limit, or when a defined time duration is reached. This is a point-in-time energy value that is measured at a defined charge voltage-current profile, discharge load profile, and temperature profile. Battery discharge can be accomplished with constant current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power. This is also sometimes called Watt-hour capacity.

$$\text{Battery Energy (Wh)} = \int I_d V_d dt$$


Energy Reserve	Total amount of usable energy in Watt-hours remaining in a battery, which has been discharged to the maximum-allowed DOD under normal operating conditions to either the minimum power subsystem battery voltage limit, or when the first cell reaches the lower cell voltage limit.
Finding	A conclusion based on facts established by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Polarization	The change of the potential of a cell or electrode from its equilibrium due to the flow of current, which typically results in higher an increase in resistance and degradation of performance.
Problem	The subject of the independent technical assessment/inspection.

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Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Qualification	The process of verifying that the product can meet the design specifications within the mission operating conditions.
Rated or Nameplate Capacity	Measured in units of Ampere-hours or Watt-hours. The rated battery capacity is provided by the battery or cell vendor and is typically less than the actual capacity. Manufacturers usually provide excess capacity over the rated value to compensate for variability within the manufacturing lot and capacity losses expected over the life of the battery.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Reversal	The changing of the normal polarity of a cell, typically due to overdischarge of the cell.
Verification	The process of checking that the product meets the specified requirements.
Wet Life	The maximum period during which a battery can deliver a specified capacity after activation.

## 10.0 Acronyms List

AL	Alabama
ATK	Alliant Techsystems Inc.
CA	California
COMSAT	Communications Satellite
DOD	Depth-of-Discharge
DPA	Destructive Physical Analysis
ESMD	Exploration Systems Mission Directorate
GA	Georgia

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GEO	Geosynchronous-Earth-Orbit
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
IEEE	Institute of Electrical and Electronics Engineers
IECEC	Intersociety Energy Conversion Engineering Conference
ISS	International Space Station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LEO	Low Earth Orbit
Li-Ion	Lithium-Ion
LM	Lockheed Martin
LM/COMSAT	Lockheed Martin/Communications Satellite Corporation
MSFC	Marshall Space Flight Center
MTSO	Management and Technical Support Office
NAFBSWG	NASA Aerospace Flight Battery Systems Working Group
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
Ni-H <sub>2</sub>	Nickel Hydrogen
NRB	NESC Review Board
NSWC/CD	Naval Surface Warfare Center/Crane Division
SMD	Science Mission Directorate
S/N	Serial Number
SOMD	Space Operations Mission Directorate
SPRT	Super Problem Resolution Team (now called Technical Discipline Team (TDT))
TAC	The Aerospace Corporation
TDT	Technical Discipline Team
US	United States
USG	United States Government
V&V	Validation and Verification
VT	Voltage/Temperature

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## Volume II: Appendices (stand-alone volume)

- Appendix A. Electrical Testing and Destructive Physical Analysis of Nickel-Hydrogen Cells with Various Storage Histories
- Appendix B. Analysis of Stored Nickel-Hydrogen Battery Cells
- Appendix C. Accelerated Cycle Test Report

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